Theory and Reality...

Field Dynamics in Superconducting (Accelerator) Magnets

Luca.Bottura@cern.ch

CAS on Superconductivity, Erice, May 8-17, 2002

T. Clancy, Carrier: a guided tour of an aircraft carrier, Berkeley Publications, 1999

Theory...

- It's 2016...
- ... nuclear war lurks between India and Pakistan ...
- ... Jill, a wonderful blonde, dicovers a new ceramic SC well above RT (Cu-Pt-Sc mix, the one that does not explode) ...
- ... large Pt and Sc reserves found in Sri-Lanka...
- ... Jill wins the Nobel Prize in Chemistry and Physics ...
- ... sees instant widespread applications of SC (B$ over B$)
- ... and saves the world from nuk'ing ...

... and Reality

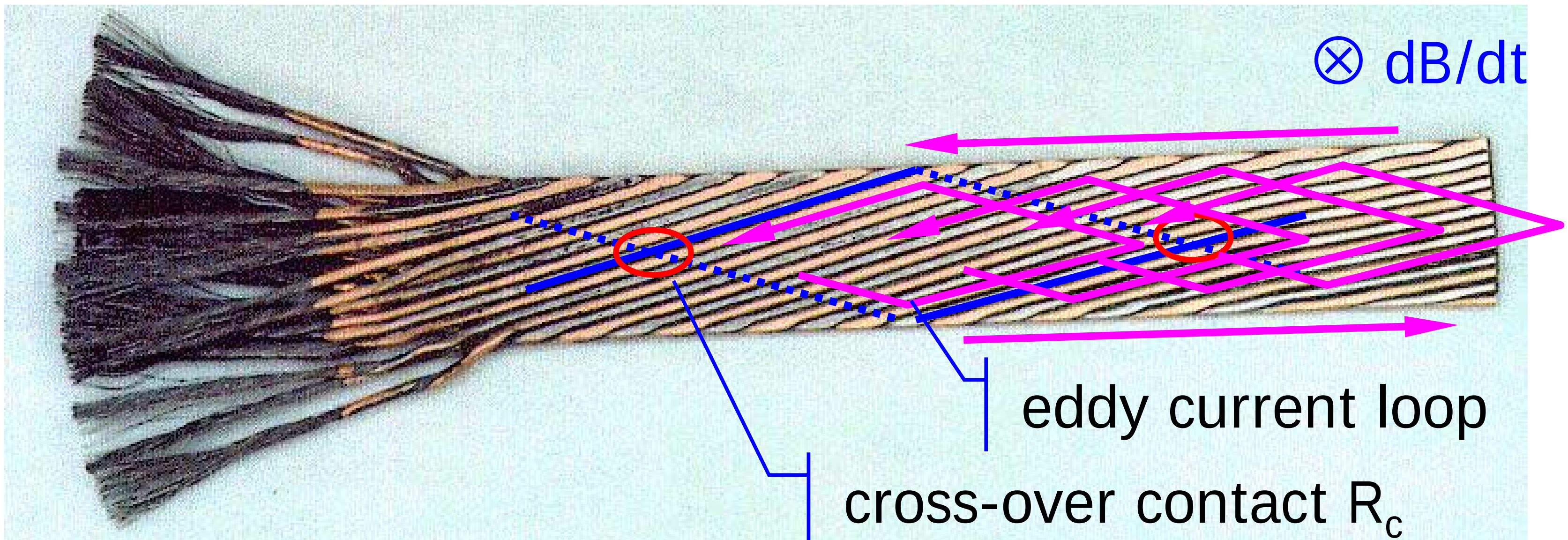
- It’s 2002...
- ... nuclear war lurks between India and Pakistan ...
- ... the workhorse of superconducting technology is (still) NbTi, discovered between ‘55 and ‘65...
- ... never awarded a Nobel Prize in Chemistry nor Physics ...
- ... the largest-scale application of superconductivity will be the LHC, costing a mere 2 B$ and scheduled to come into operation for 2007 (theory or reality ?) ...
- ... will it save the world from nuk’ing ? Maybe !

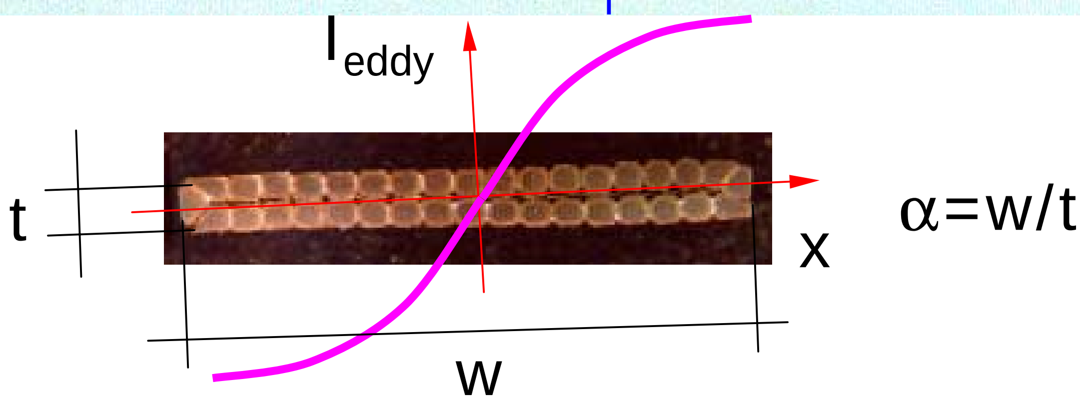
Plan of the lecture:

- Look at accelerator magnets and demonstrate by examples (reality):
  - Coupling current effects
  - Current distribution
  - Field decay and snap-back in accelerator magnets
- These effects are important when looking at
  - *high precision* (better than 0.1 %)
  - *extreme* operating conditions (high ramp-rate)
  - because they affect *reproducibility*
- A virtual reality demo

Cable coupling currents

- SC Rutherford cable in transverse field





Cable coupling currents

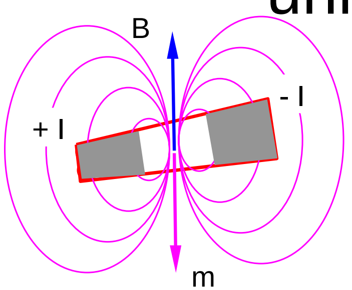
LHC cable (w=15 mm, t=2 mm, α=7.5) with R_c=15 $\mu\Omega$ and dB/dt = 7 mT/s:

- Eddy current I_{eddy} (A):

$$I_{eddy} = 41.5\times10^{-3}\frac{L_p w N}{R_c}\dot{B}_\perp \cos\left(\frac{\pi x}{w}\right)$$

$I_{eddy} \approx 0.8$ A

- Magnetic moment per unit volume M_{eddy} (T):



$$M \approx \mu_0 L_p\left[\frac{N(N-1)}{120}\frac{\alpha}{R_c}\right]\dot{B}_\perp$$

$M_{eddy} \approx 3$ mT

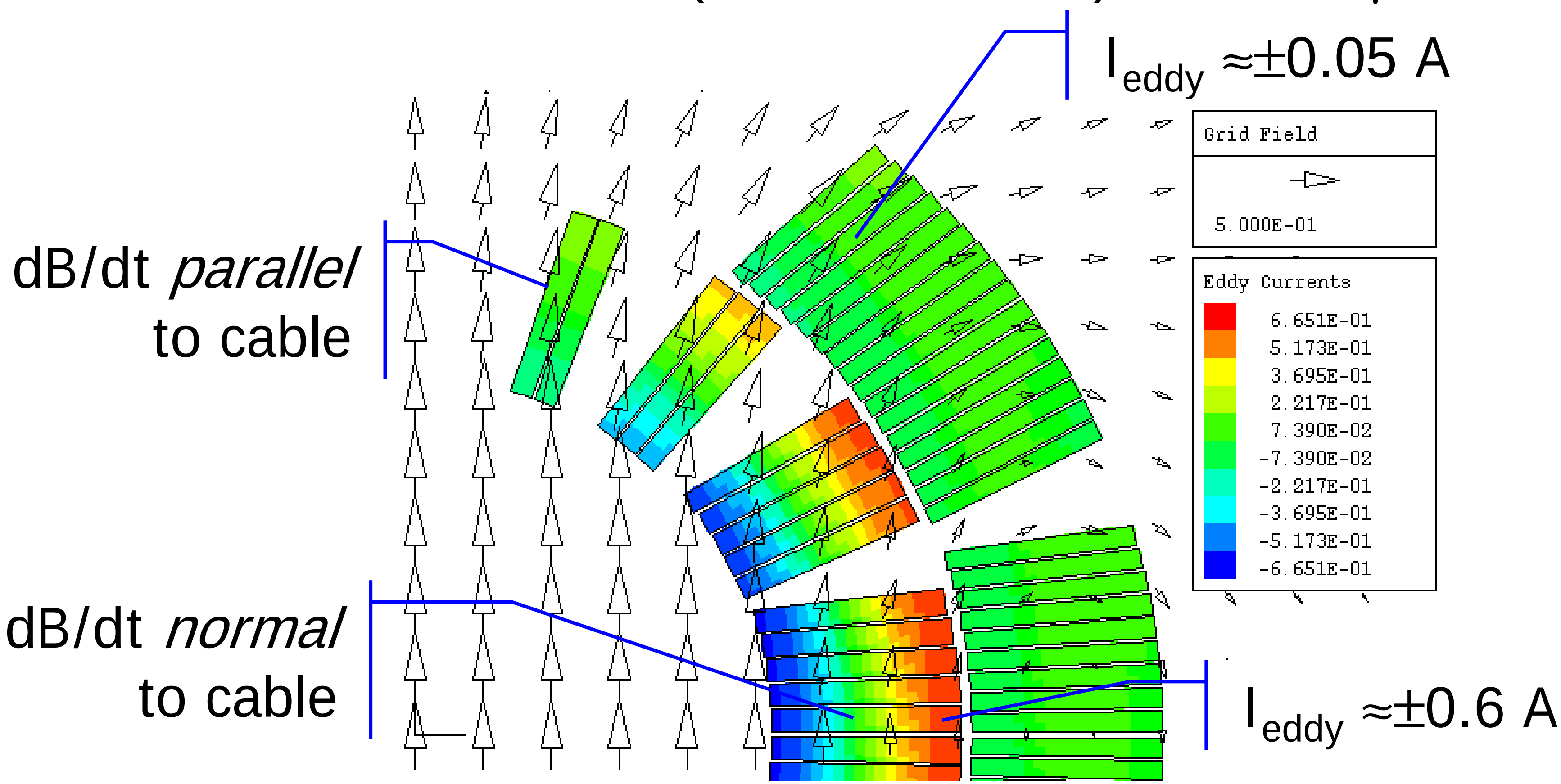
- Heat loss P_{eddy} (W/m):

$$P_{eddy} = 8.5\times10^{-3}\frac{L_p w^2 N(N-1)}{R_c}\dot{B}_\perp^2$$

$P_{eddy} \approx 0.5$ mW/m

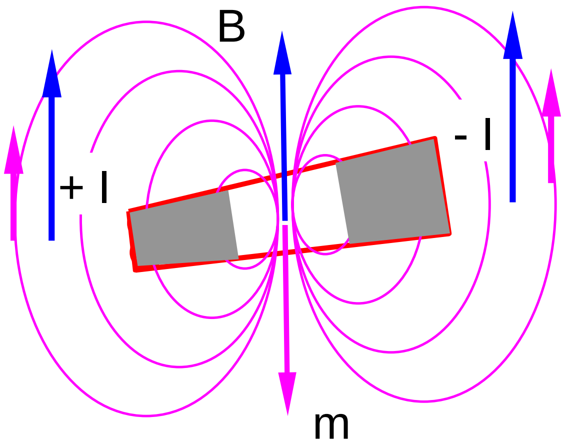
Coupling currents in a magnet

- eddy currents in a LHC dipole (inner layer)
  - $dI/dt = 10$ A/s ($dB/dt \approx 7$ mT/s), $R_c = 15\ \mu\Omega$

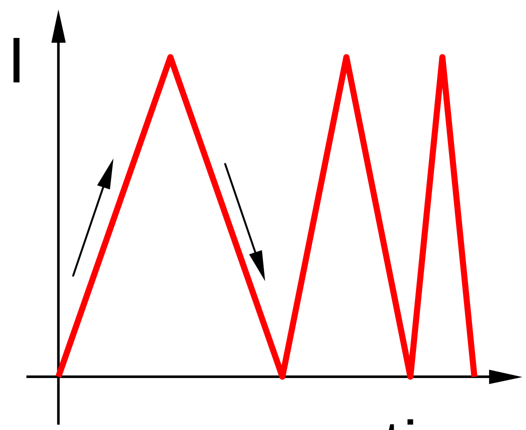


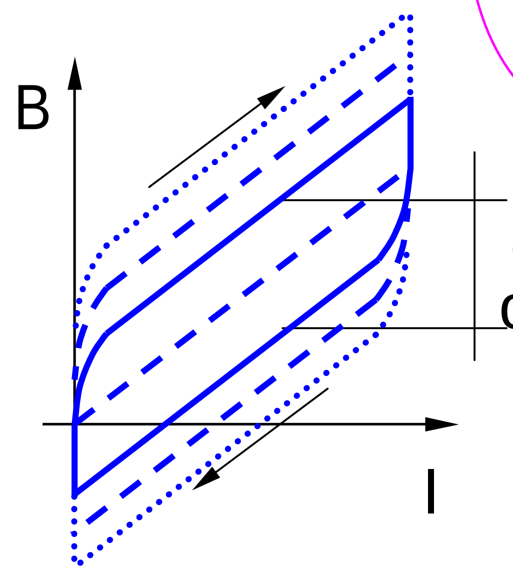
Field *advance*

- M_{eddy} generates a field that adds to the background field (*advance*) proportional to:
  - dB/dt
  - $1/R_c$



linear ramps

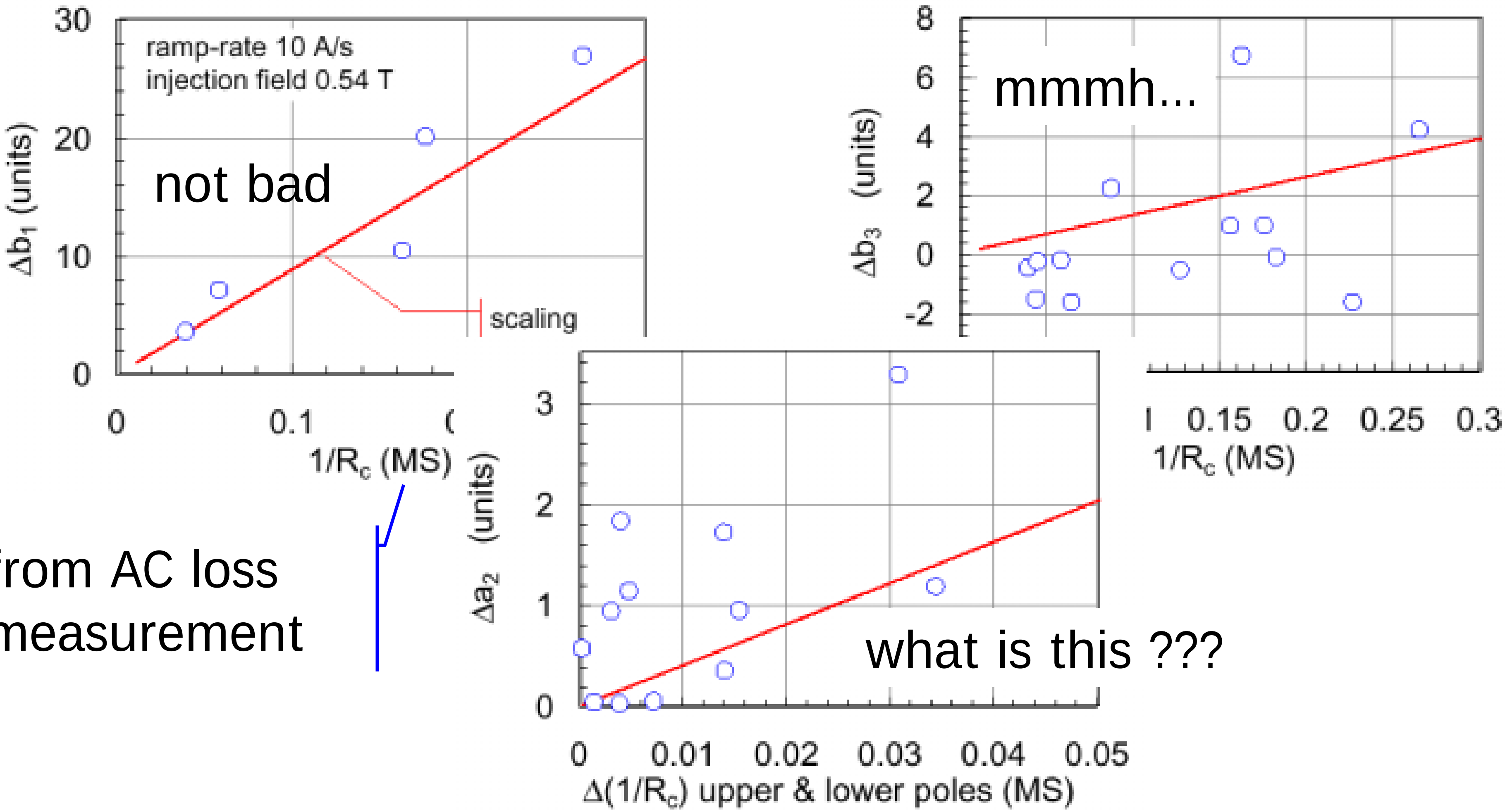




$2\Delta B(dB/dt, 1/R_c)$
order of few 10^{-4}

Field and harmonics

- loss and field measurements in LHC models

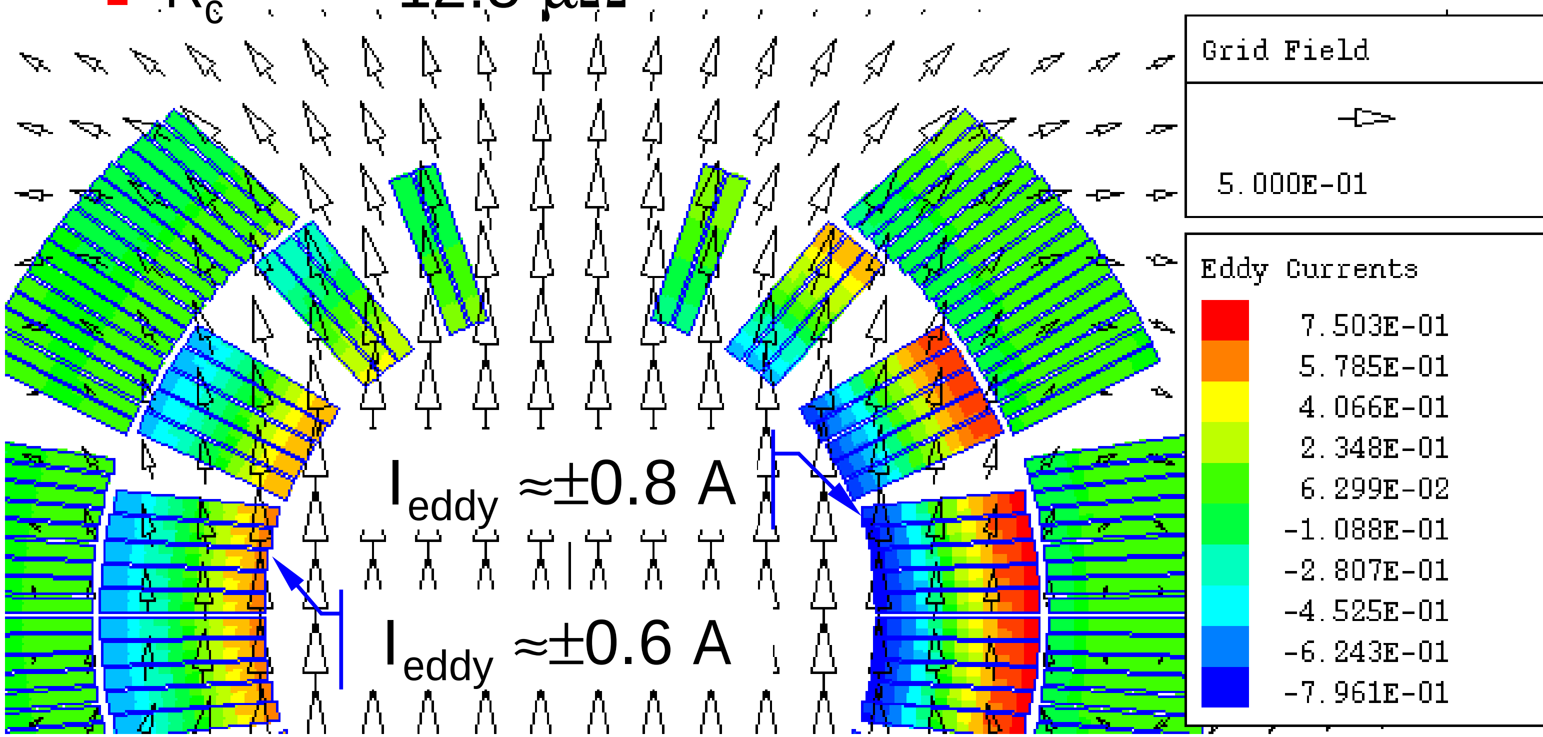


from AC loss measurement

R_c distribution

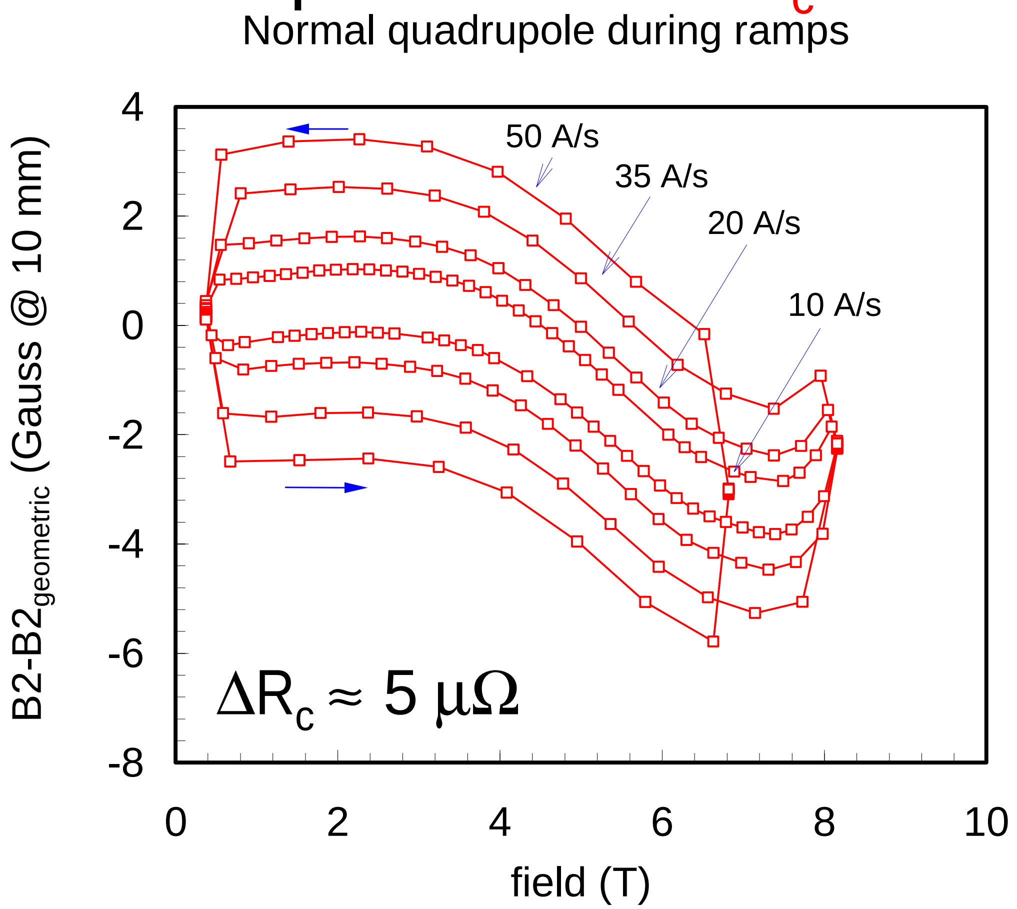
- eddy current in a LHC dipole with R_c variations
  - $dI/dt = 10$ A/s ($dB/dt \approx 7$ mT/s)
  - $R_c^{left} = 17.5\ \mu\Omega$
  - $R_c^{right} = 12.5\ \mu\Omega$

right-left asymmetric



Non-allowed harmonics

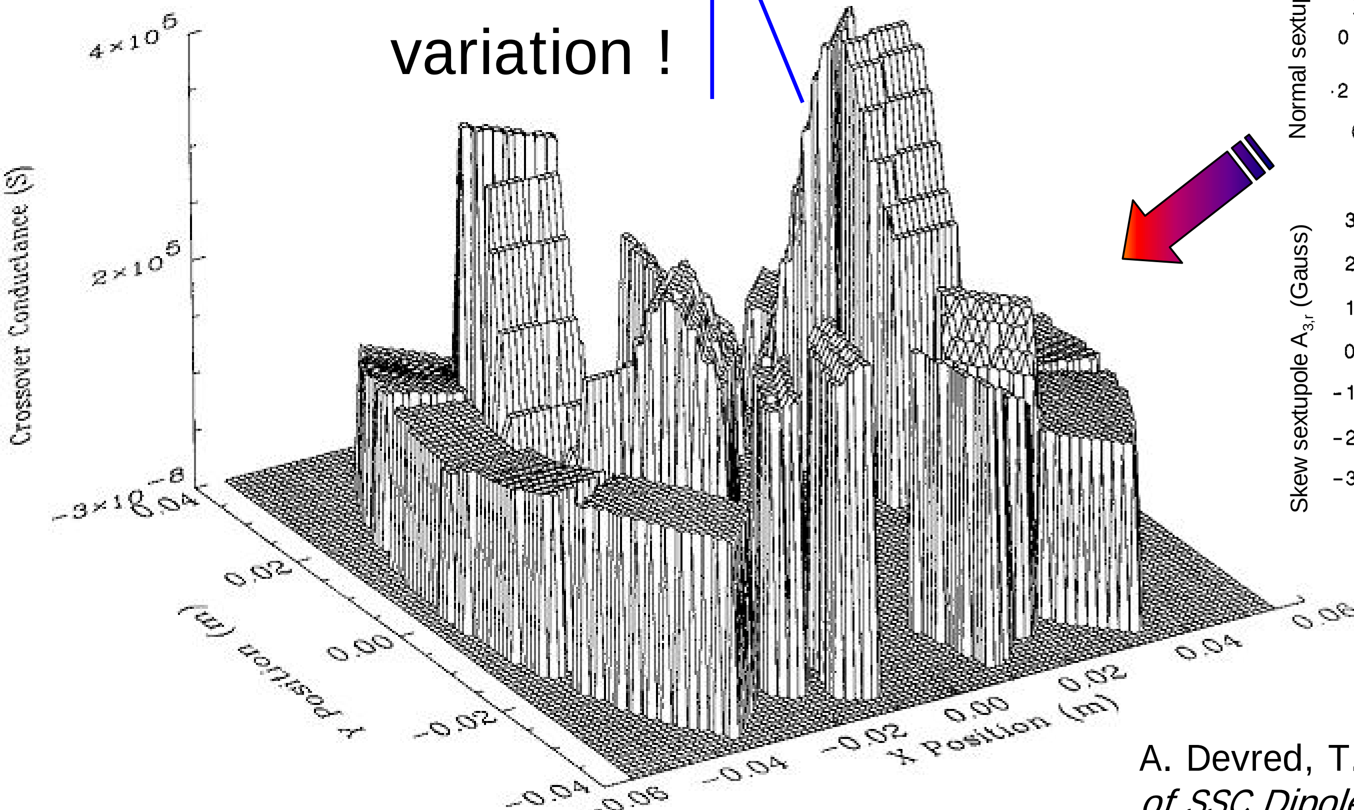
- non-allowed harmonics are produced, their magnitude depends on the R_c distribution

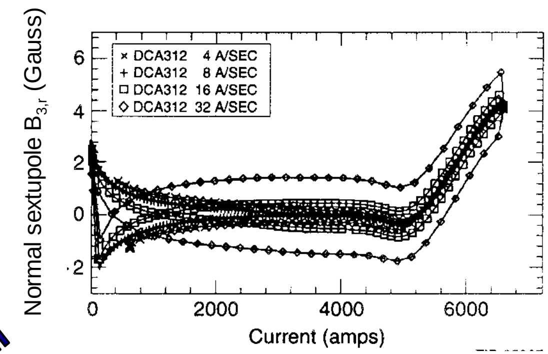


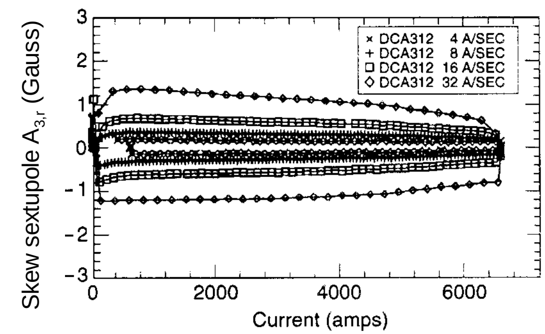
Reverse engineering...

SSC dipole prototype DCA312

as much as a factor 5 variation !





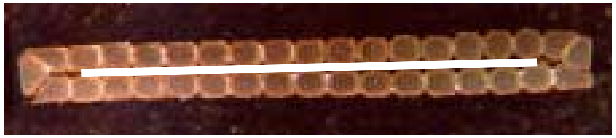


A. Devred, T. Ogitsu, *Ramp rate sensitivity of SSC Dipole Magnet Prototypes*, Frontiers of Accelerator Magnet Technology, World Scientific, 184, 1996

variation in z can also be significant

Why is it important ?

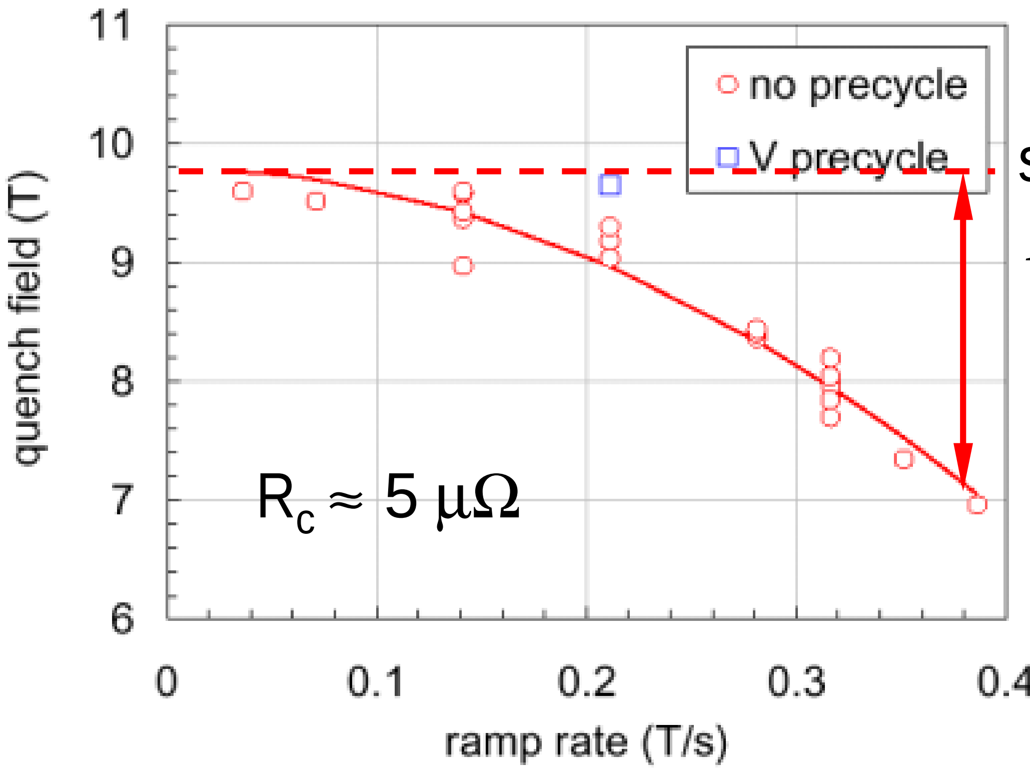
- field distortion is a headache for HEP
  - LHC dipoles during 10 A/s ramps and R_c = 15 $\mu\Omega$
    - $\Delta b_1 = 5.4 \times 10^{-4} \rightarrow \Delta Q$ = 0.054 vs. 0.003 allowed
    - $\Delta b_3 = 1.0 \times 10^{-4} \rightarrow \Delta\xi$ = 52 vs. 1 allowed
- solution
  - tolerate and correct (measure, measure, measure ...)
  - slow-down (remember dB/dt dependence) ...
  - R_c control, e.g. LHC R_c > 15 $\mu\Omega$, aiming at 20 $\mu\Omega$
    - Ag-Sn, Sn-Pb, Cu-Ni, Ni, Cr-coatings (few μm, bath or electrodeposition)
    - Cu-oxide formation (ageing of cable in a *humid warehouse*)
    - dirt, Mobil-1, soap
    - core for a Rutherford cable



    - any brighter ideas ? Must be compatible with manufacturing process !

And other effects !

- AC loss heat load



short sample limit

$$B_{quench} \propto T_{cs} - T_{op} =$$

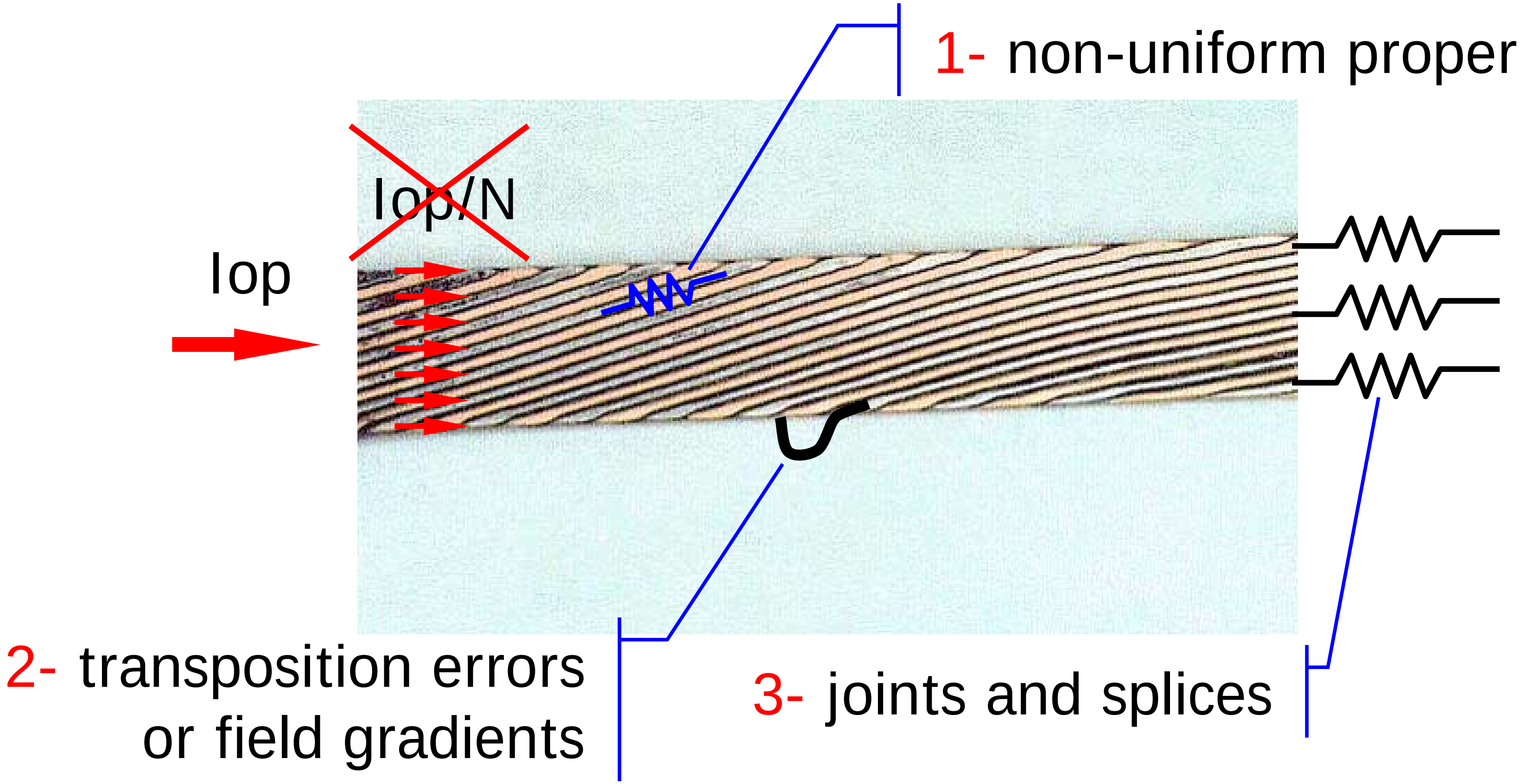
$$= T_{cs} - \left(T_o + \frac{P_{eddy}}{C} \right) =$$

$$= \alpha - \beta \dot{B}_{\perp}^2$$

(provisional) conclusion – keep Rc as high as possible !
insulate strands ?

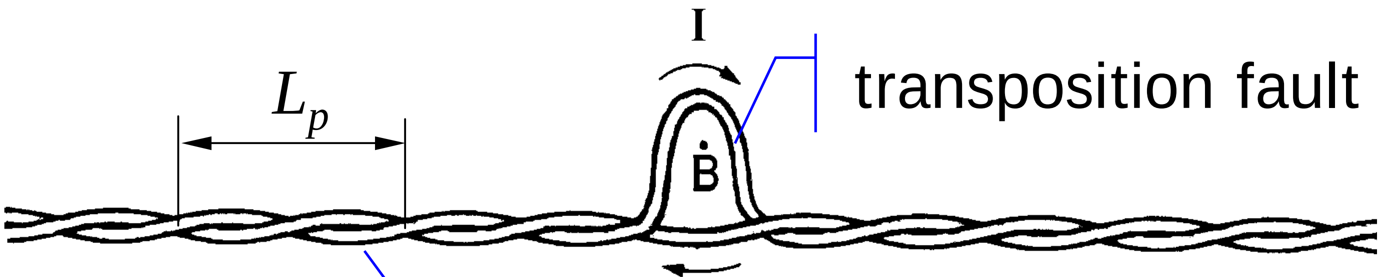
Current distribution

- the strands in a multi-strand cables <u>never</u> carry the same current – why ?



A simple case

- simple situation: two-strands cable with a transposition fault linking a flux ψ

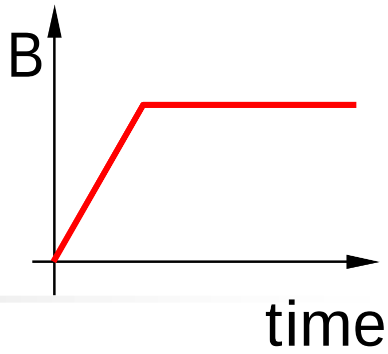


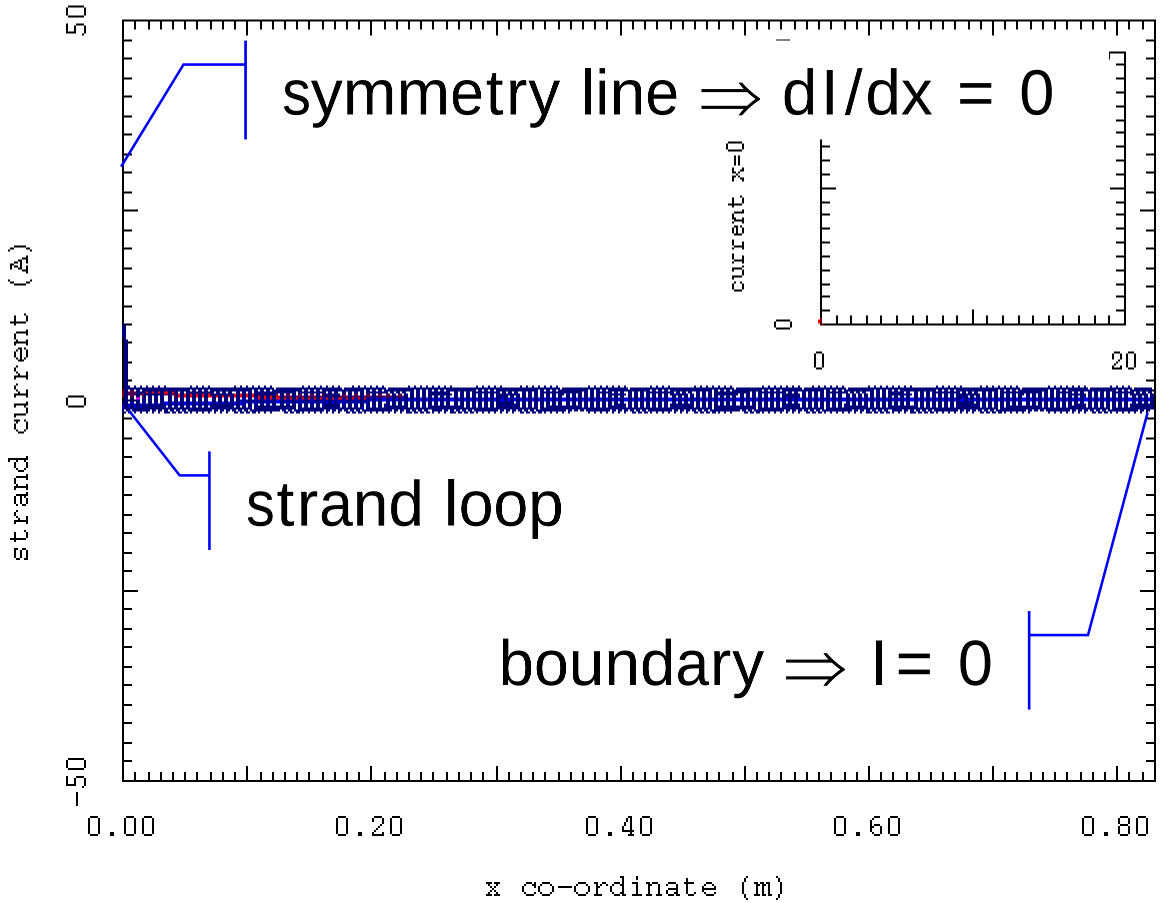
transposition fault

length L
inductance l (self), m (mutual)
transverse conductance $g=2/(R_c L_p)$

- a field ramp generates parasite *super*currents with long range and long time constant

Field Ramp





current distribution from other origins (joints, Ic) has similar effects

Scalings

- amplitude of the *super*currents:

linear scaling with L

linear scaling with $1/R_c$

$$I_{super} = \frac{L\,\psi}{2R_c L_p}$$

- time constant:

quadratic scaling with L

$$\tau = \frac{4(l-m)}{R_c L_p}\left(\frac{L}{\pi}\right)^2$$

linear scaling with $1/R_c$

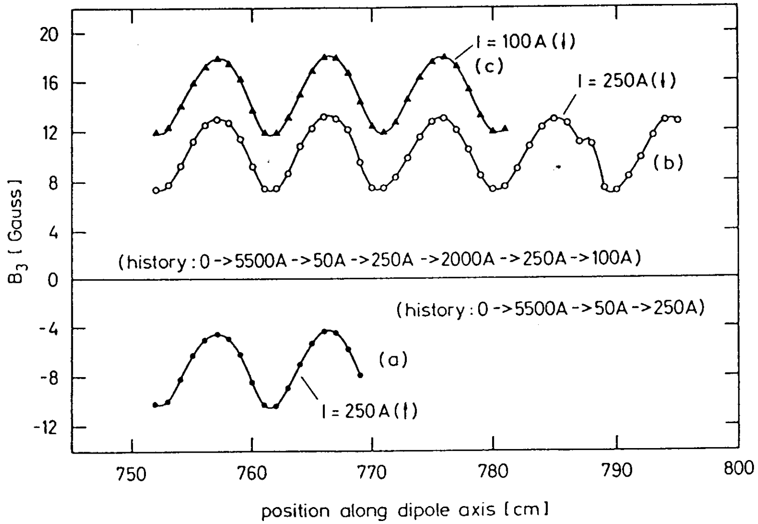
times can be extremely long (hours, days, months, years)

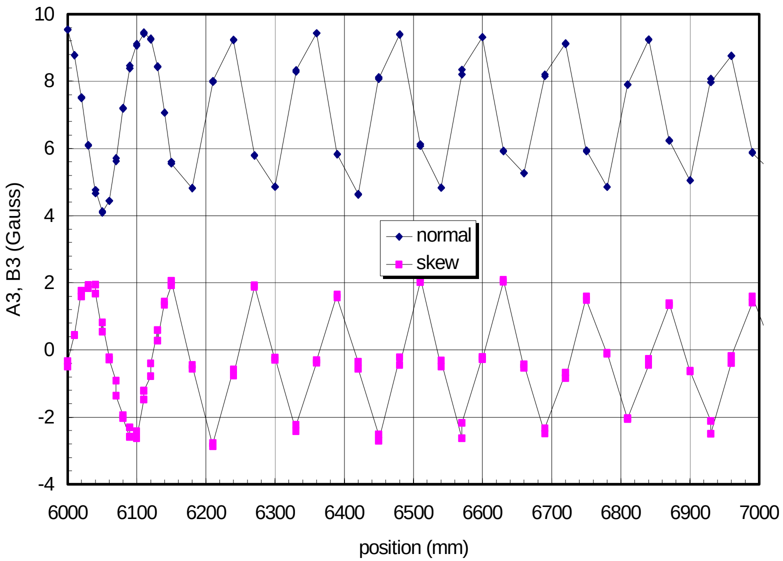
the current is frozen in the strands

Something strange ...

- periodic field pattern observed along the length of a HERA dipole magnet ...

- ... appearing in all magnets, on all harmonics (SSC, RHIC, LHC) ...





It's current distribution !

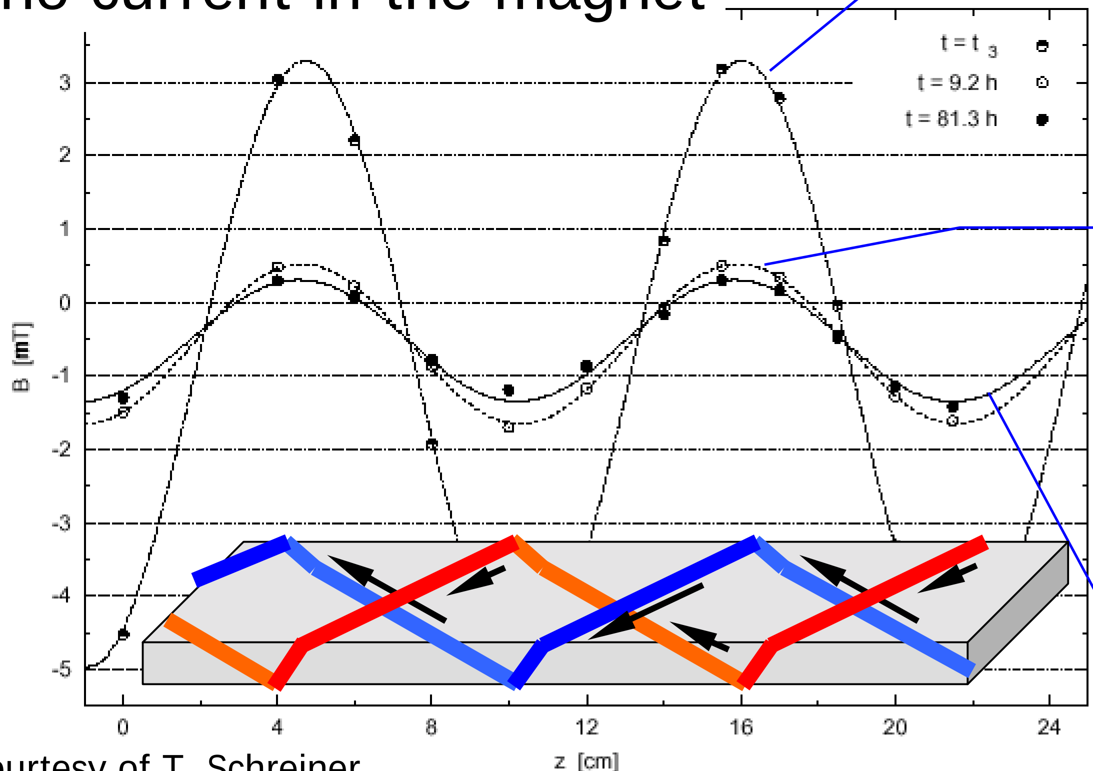
- ... evolves and decays over time constants of several 100's to 1000's seconds...

no current in the magnet

right after a pre-cycle to I_{nom} and ramp to 0

after 9 hours

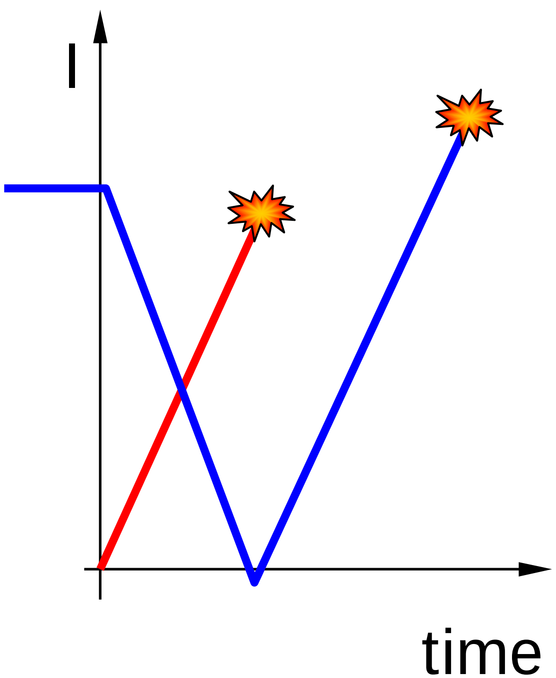
after 81 hours

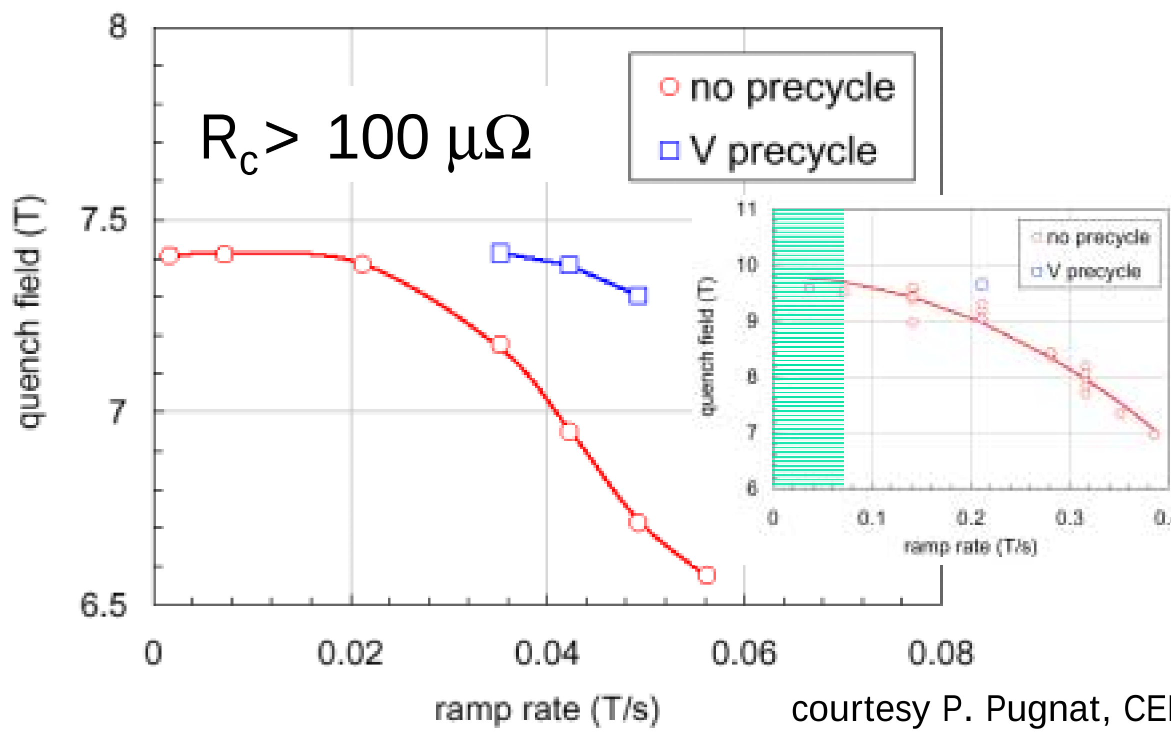


courtesy of T. Schreiner

Why is it important ?

- early current sharing and premature quench
  - *type-A* and *type-B* behaviour in SSC dipoles
  - large ramp-rate dependence and pre-cycle influence in LHC dipoles





courtesy P. Pugnat, CERN

There is more than HEP...

- Ramp-rate limitation (RRL) in fusion magnets
  - Japanese Demonstration Poloidal Coil (DPC-U1, DPC-U2) showed *catastrophic* RRL
  - RRL observed in US-DPC above $I_{limiting}$

quench current

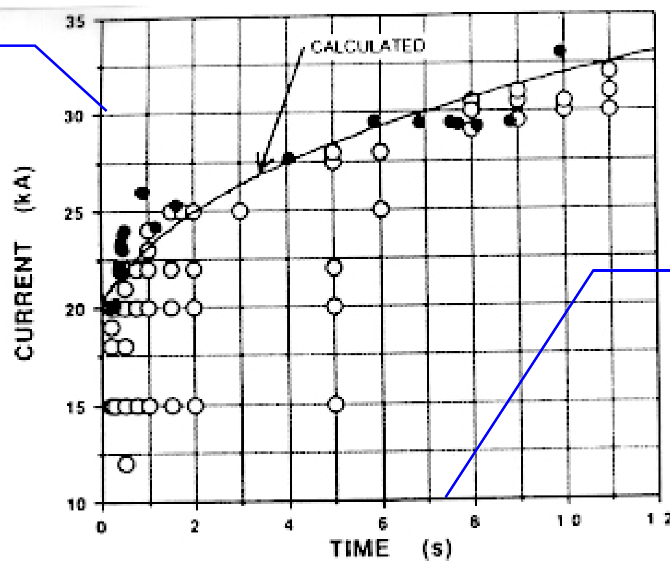


Fig. 1 Ramp-rate limitation of US-DPC operating alone. Solid circles indicate quenches and open circles no-quenches. The solid curve was calculated from Eq. (16).

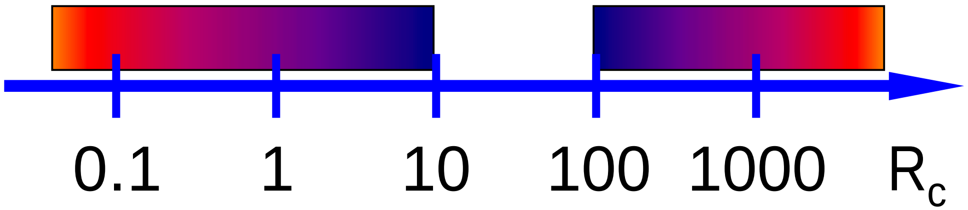
● quench
○ no quench

ramp-time, inversely proportional to dB/dt

M. Takayasu, et al., IEEE Trans. Appl. Sup., **3**(1), 456-459, 1993

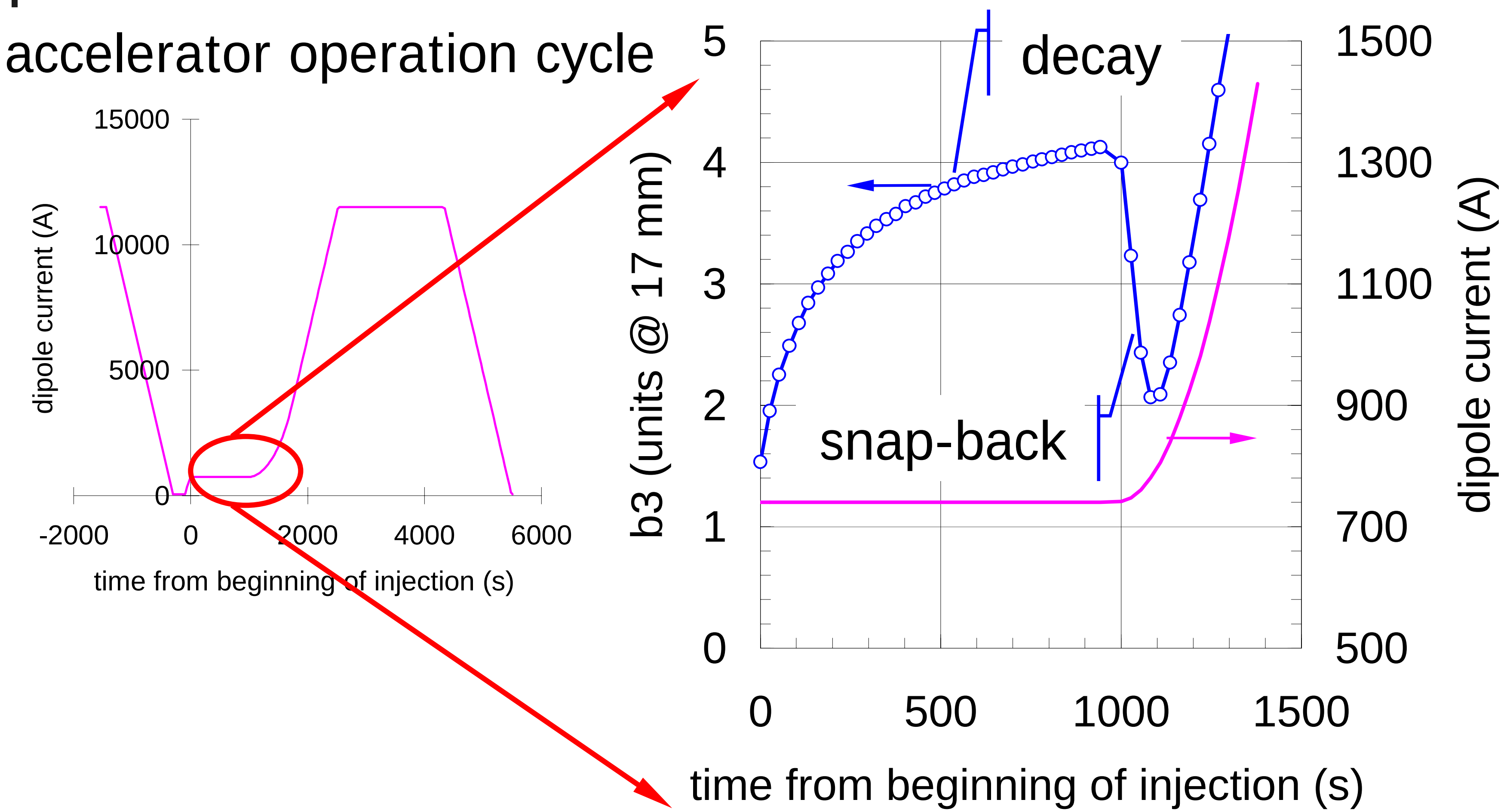
So what ?

- do not make R_c too small ($\ll 10\ \mu\Omega$)
  - AC loss
  - quench because of excessive heating
  - field distortions
- do not make R_c too large ($\gg 100\ \mu\Omega$)
  - (frozen) current cannot re-distribute and can cause premature quenches

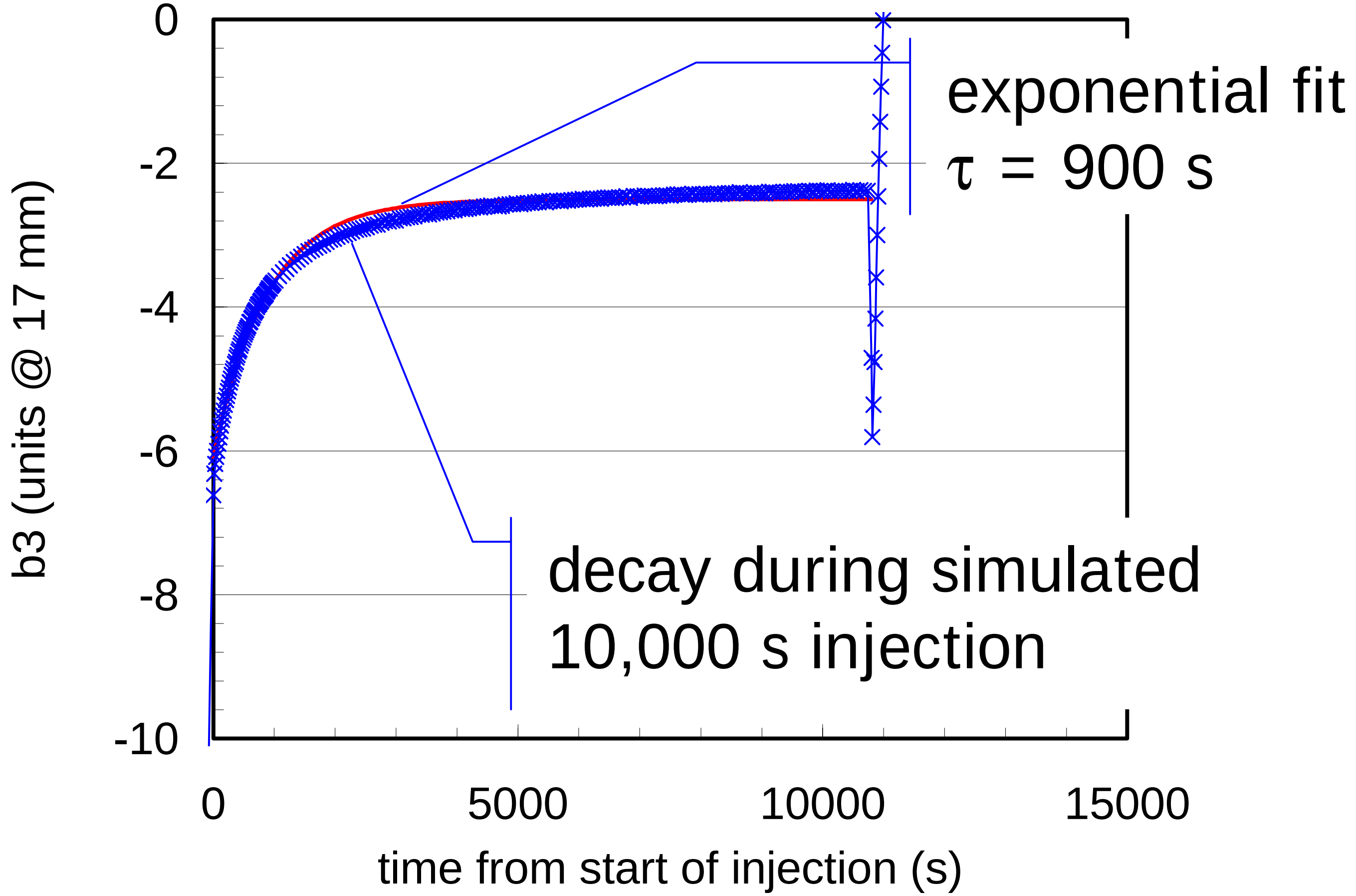


is this all ? NO !

Decay and Snap-back



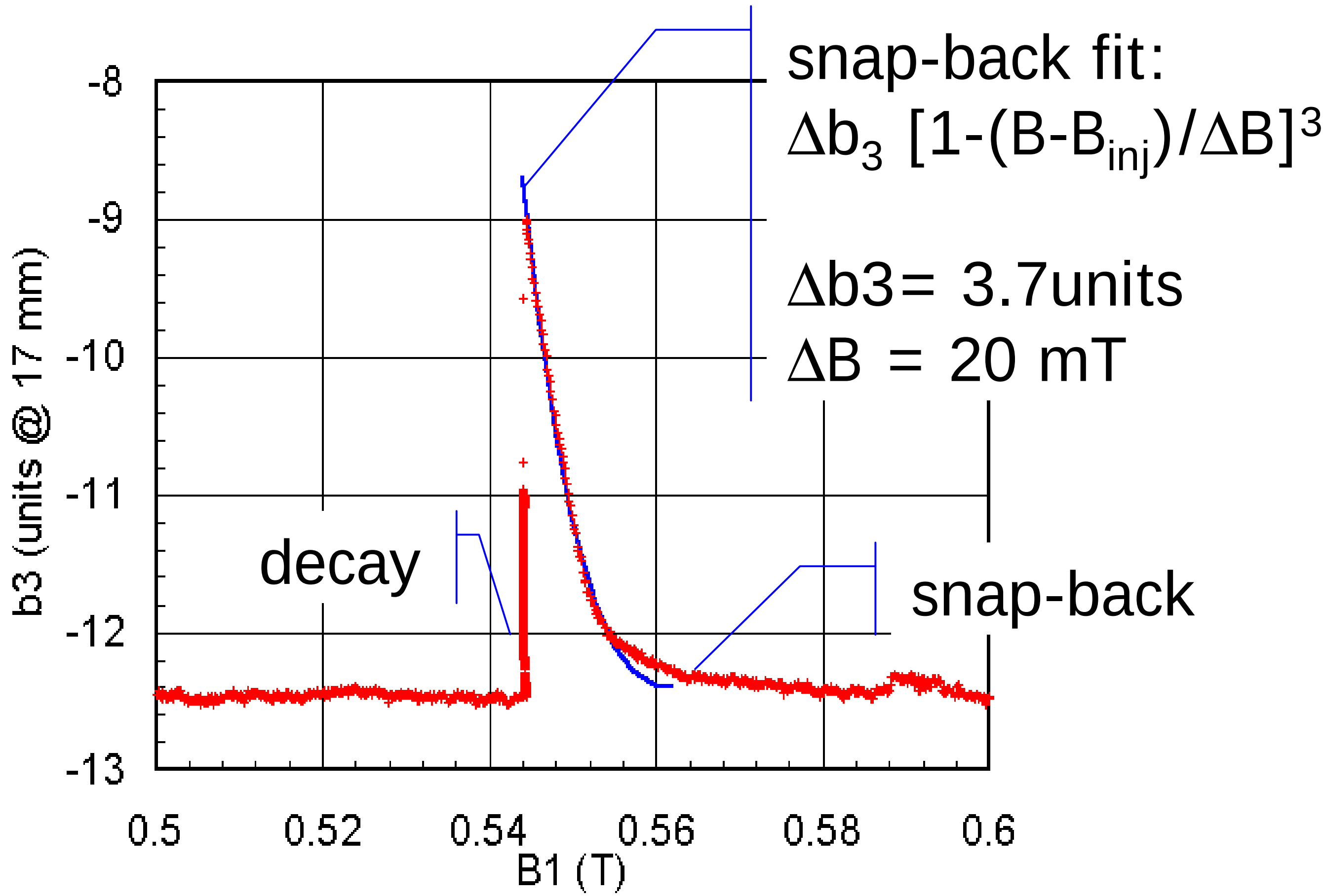
Decay



long time constant (minutes, hours, days)

resembles suspiciously current distribution

Snap-back

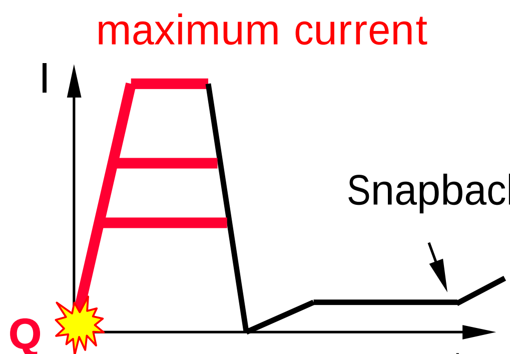


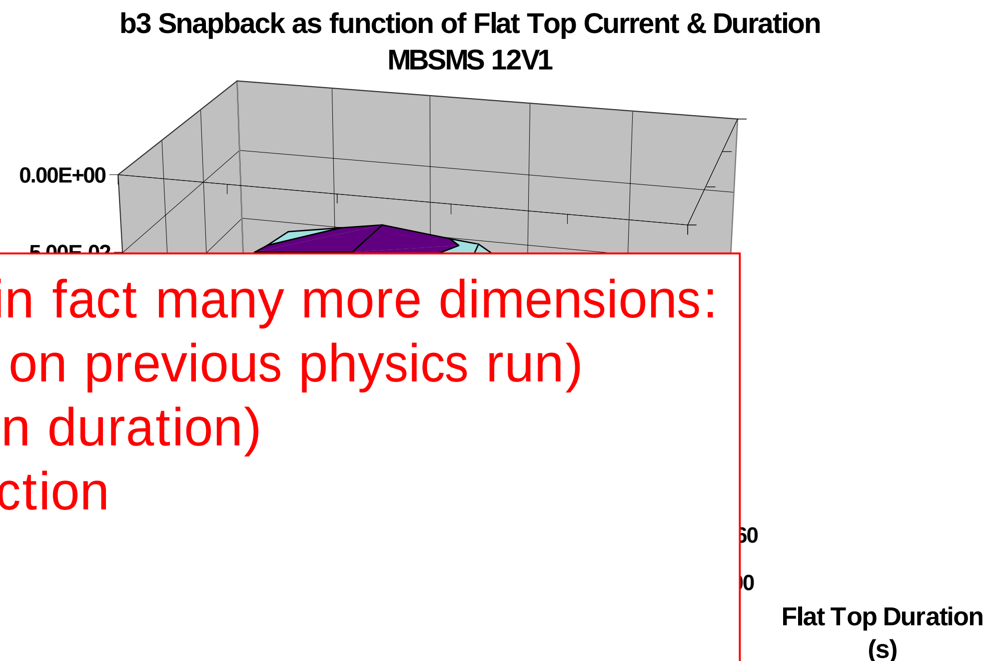
cubic dependence on field change

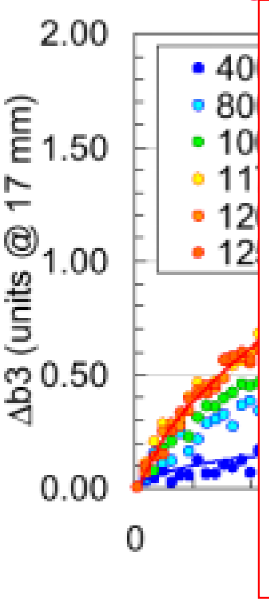
resembles suspiciously penetration of a SC filament

History and memory

- decay and SB depend on the powering history





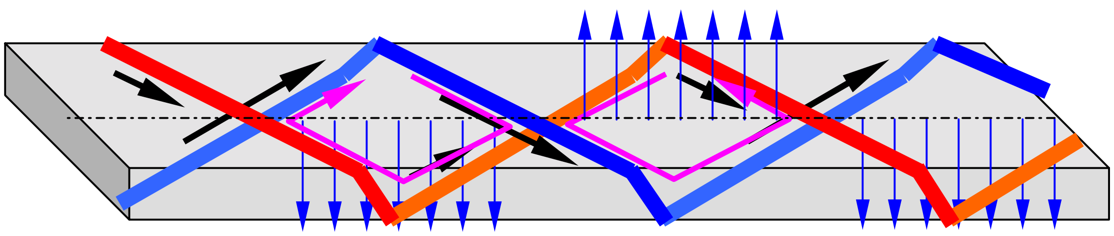


the parameters space has in fact many more dimensions:
- flat-top current (energy on previous physics run)
- flat-top time (physics run duration)
- waiting time before injection
- ramp-rates (up, down)
- cycles repetition
- temperature
- quench/no quench ...

7-dimensional space... machine reproducibility ???

One ...

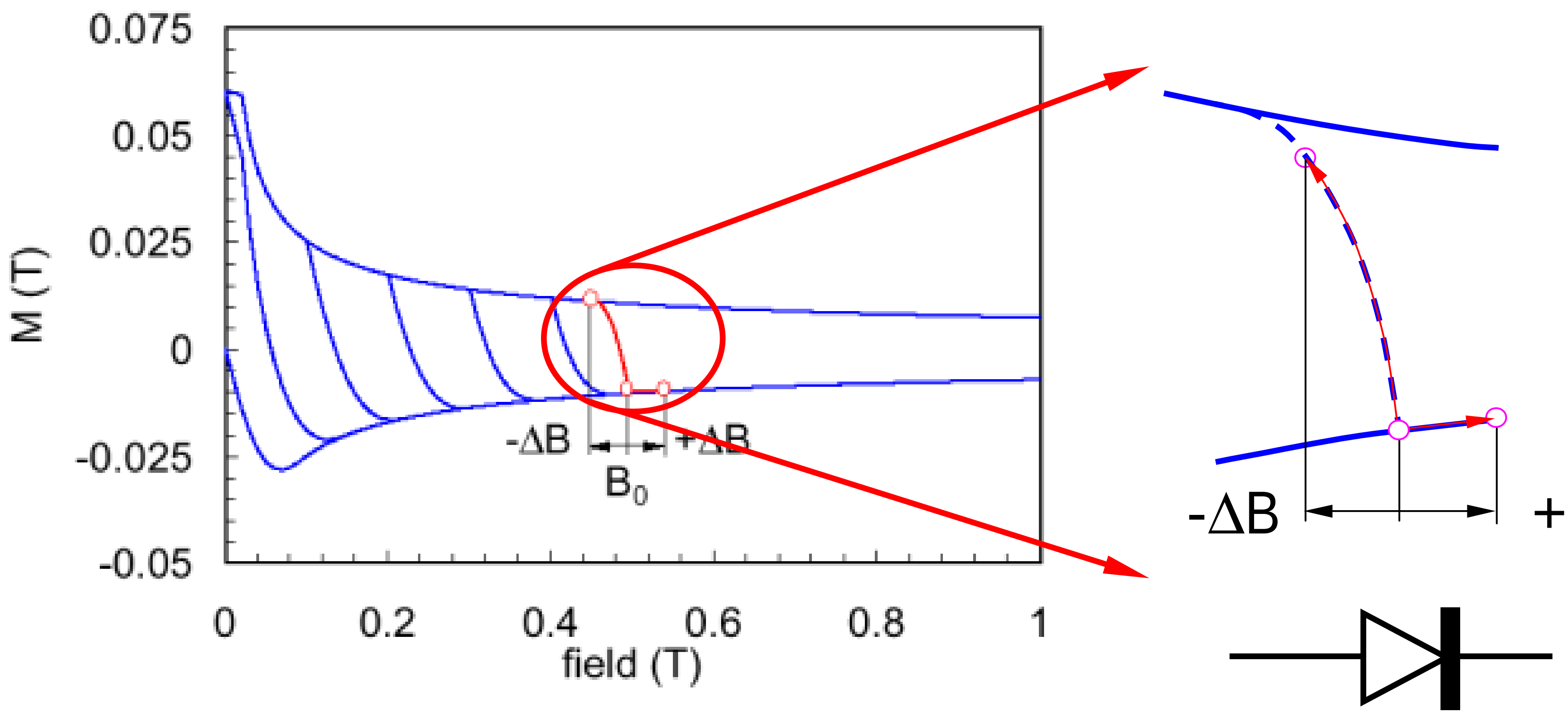
- Current distribution is not uniform in the cables...
- ...and changes as a function of time generating a time-variable, alternating field along the strands...



R. Stiening, SSC
R. Wolf, CERN

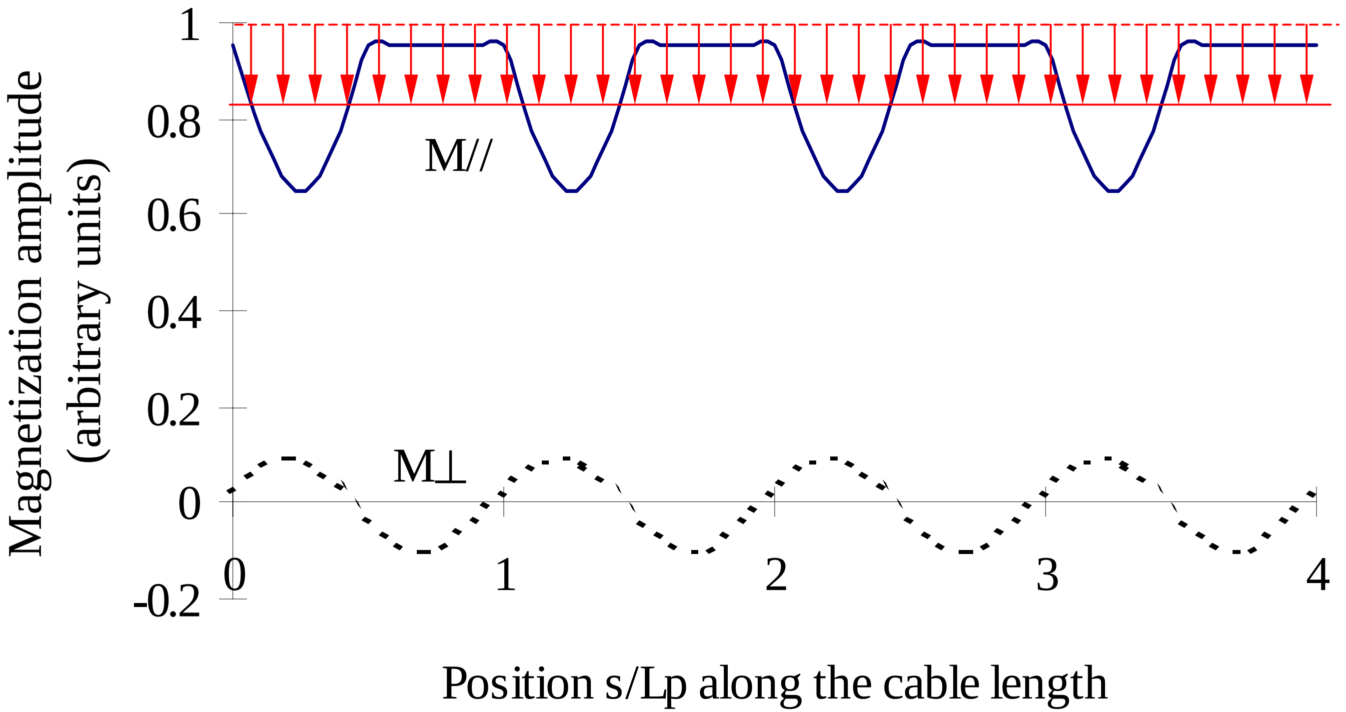
... two ...

- ...the field change affects the magnetization of the super-conducting filaments...



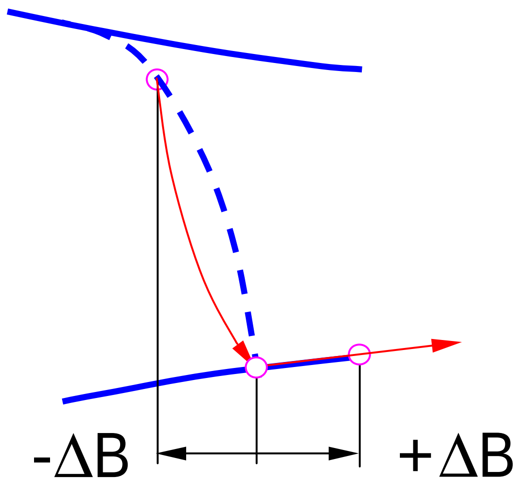
… three …

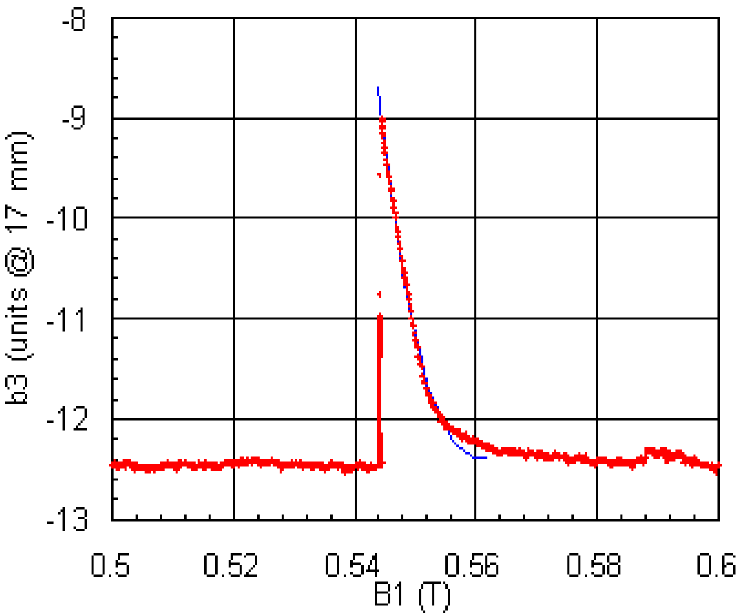
- and the magnetization change averages to a net decrease (rectifying effect) – the decay !



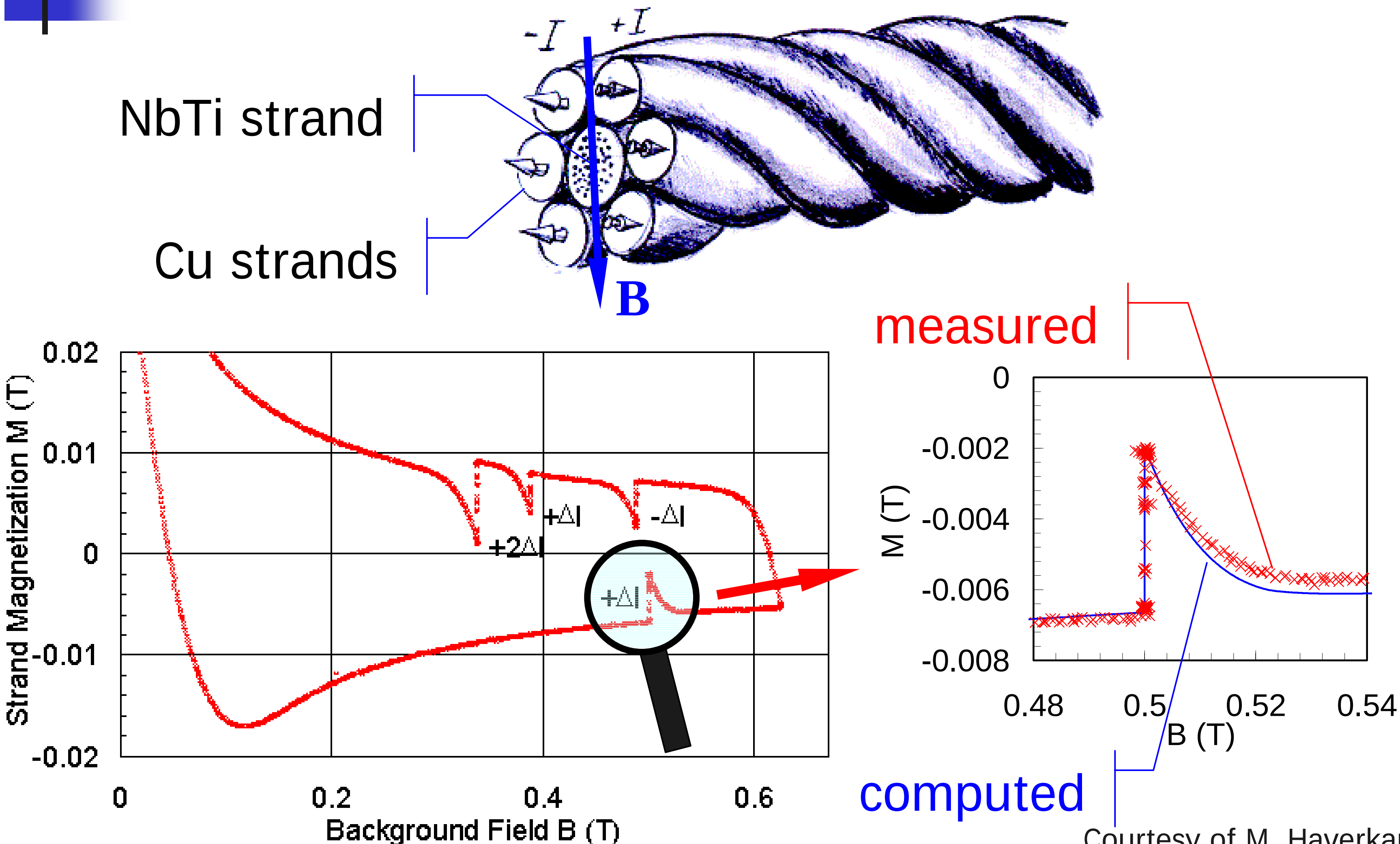
... et voilà !

- The magnetization state is re-established as soon as the background field is increased by the same order of the internal field change in the cable (5 to 30 mT) – the snap-back !



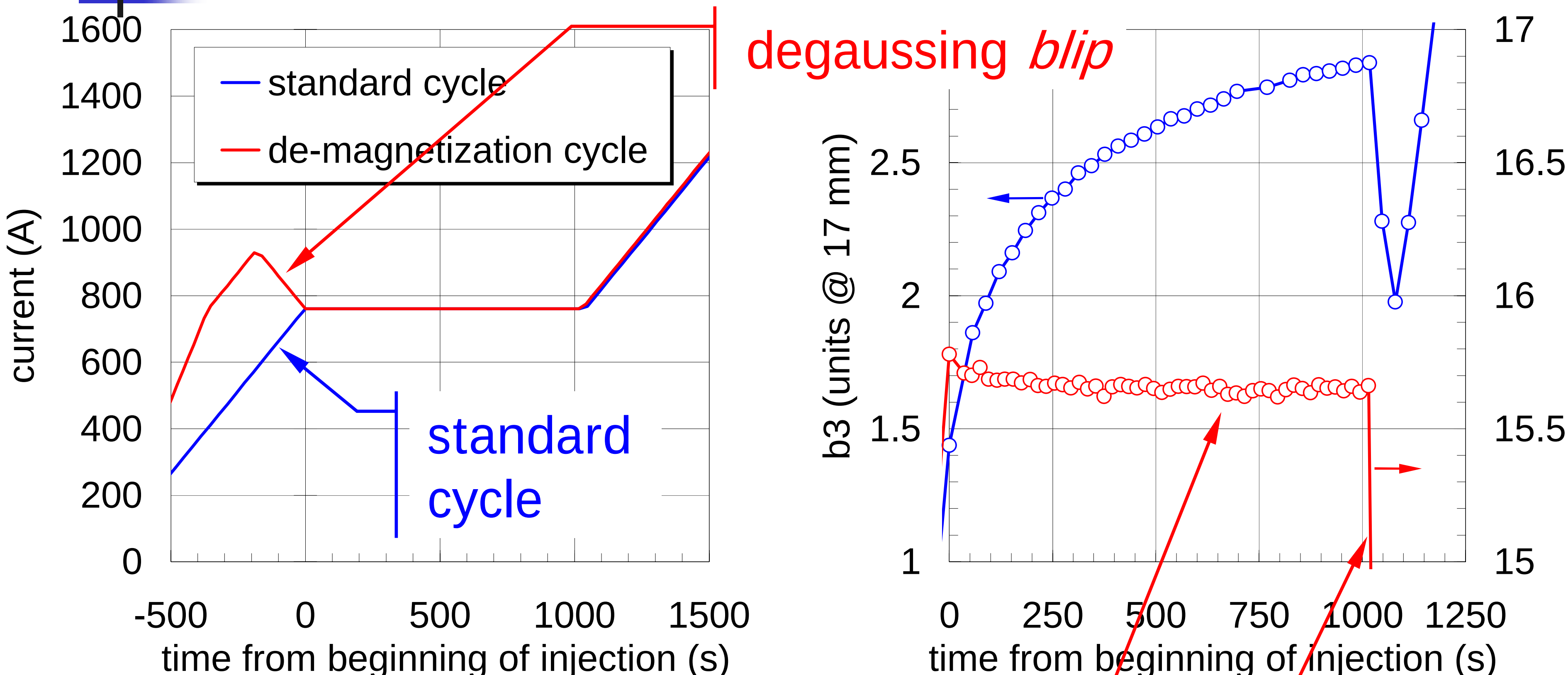


A demonstration experiment



Courtesy of M. Haverkamp
experiment performed at U. Twente

Ideas - *Degaussing* LHC



negligible decay after degaussing...

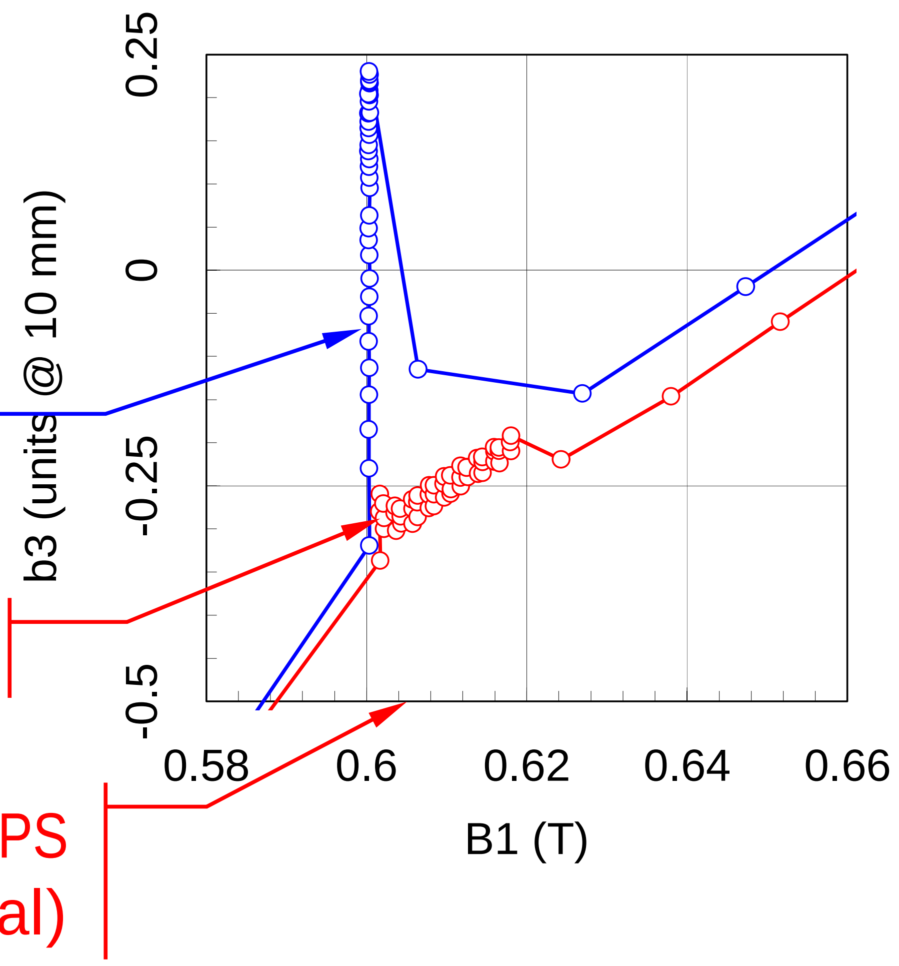
... but useless for operation (*giant* 11 units SB)!

OK for injection tests ?

Ideas - *LHC on the Fly*

- Continuous ramp at injection:

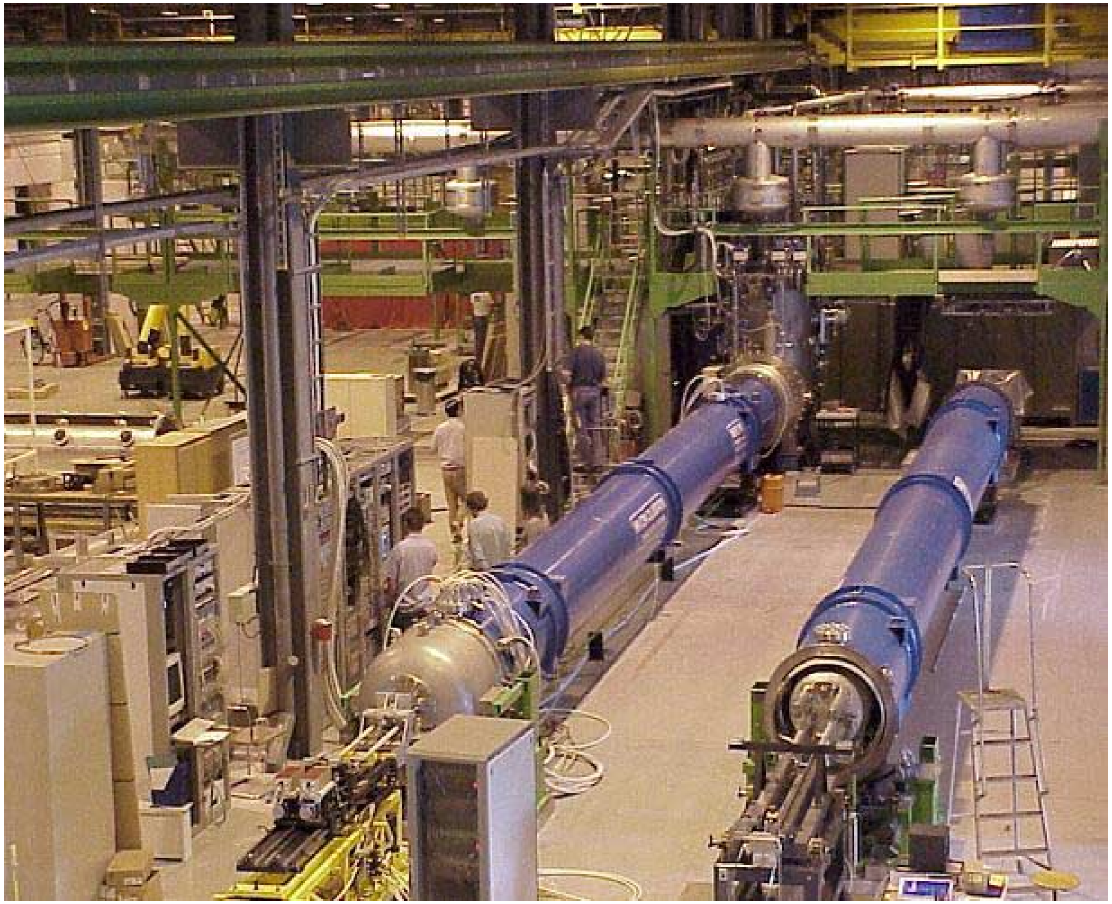
  20 mT in 20 min



Conclusions – Part I

- many complex effects can be understood using *simple* electromagnetism and appropriate tools
- prediction and control are however a challenge
  - a SC magnet is a bit like a weather report
    - Mega-multi-variable systems, e.g. 35 M-R_c's in an LHC dipole
    - difficult to model if you do not know where to start from !
  - production control only partially available (I_c, R_c, ...)
  - some effects cannot be avoided, e.g. the inhomogeneous current distribution, decay and SB
- extensive measurements are mandatory

Measure, measure, measure...

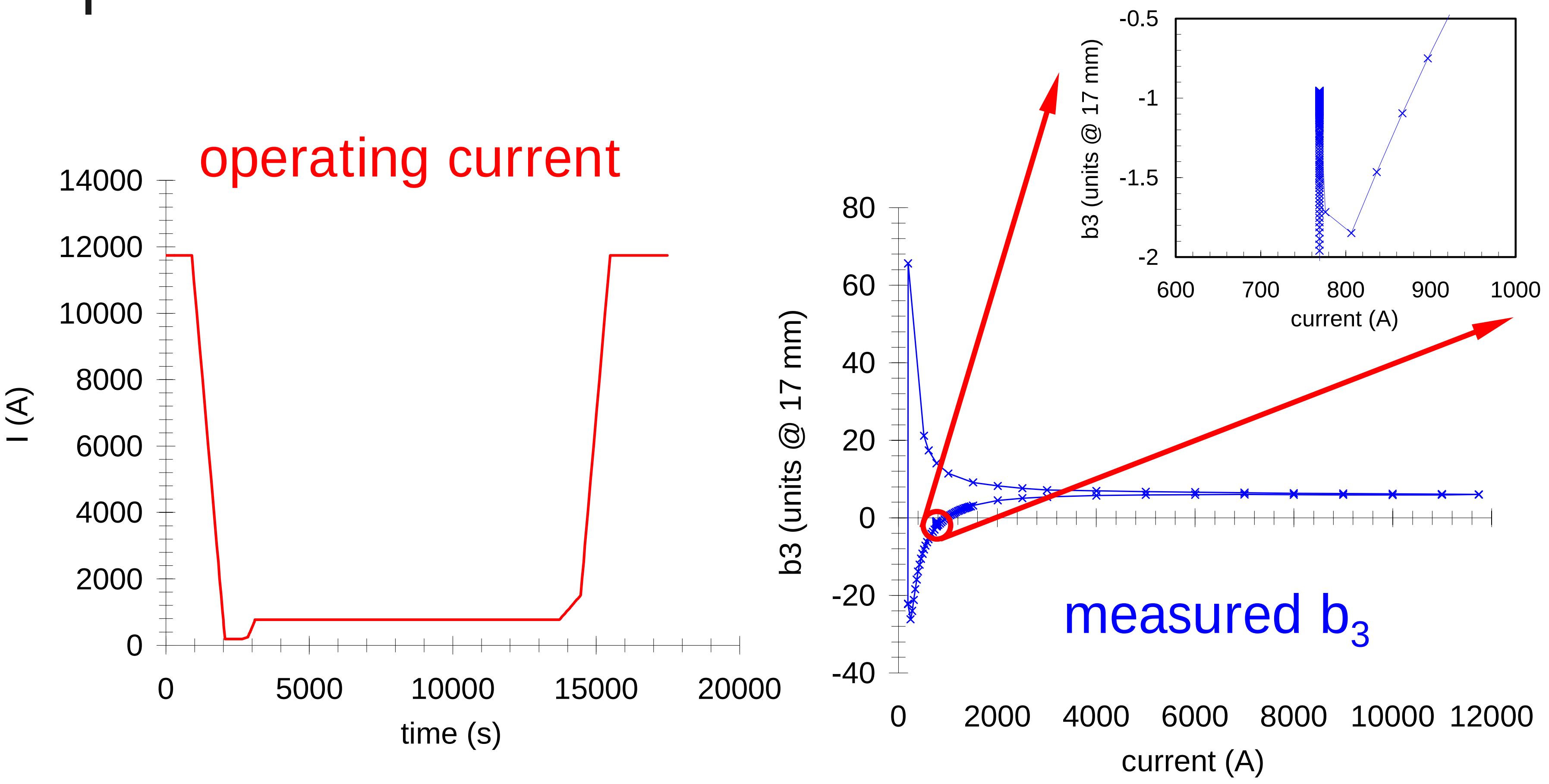


multi-MCHF project for the characterization of the LHC magnets and the operation of the LHC (*Multipoles-Factory*)

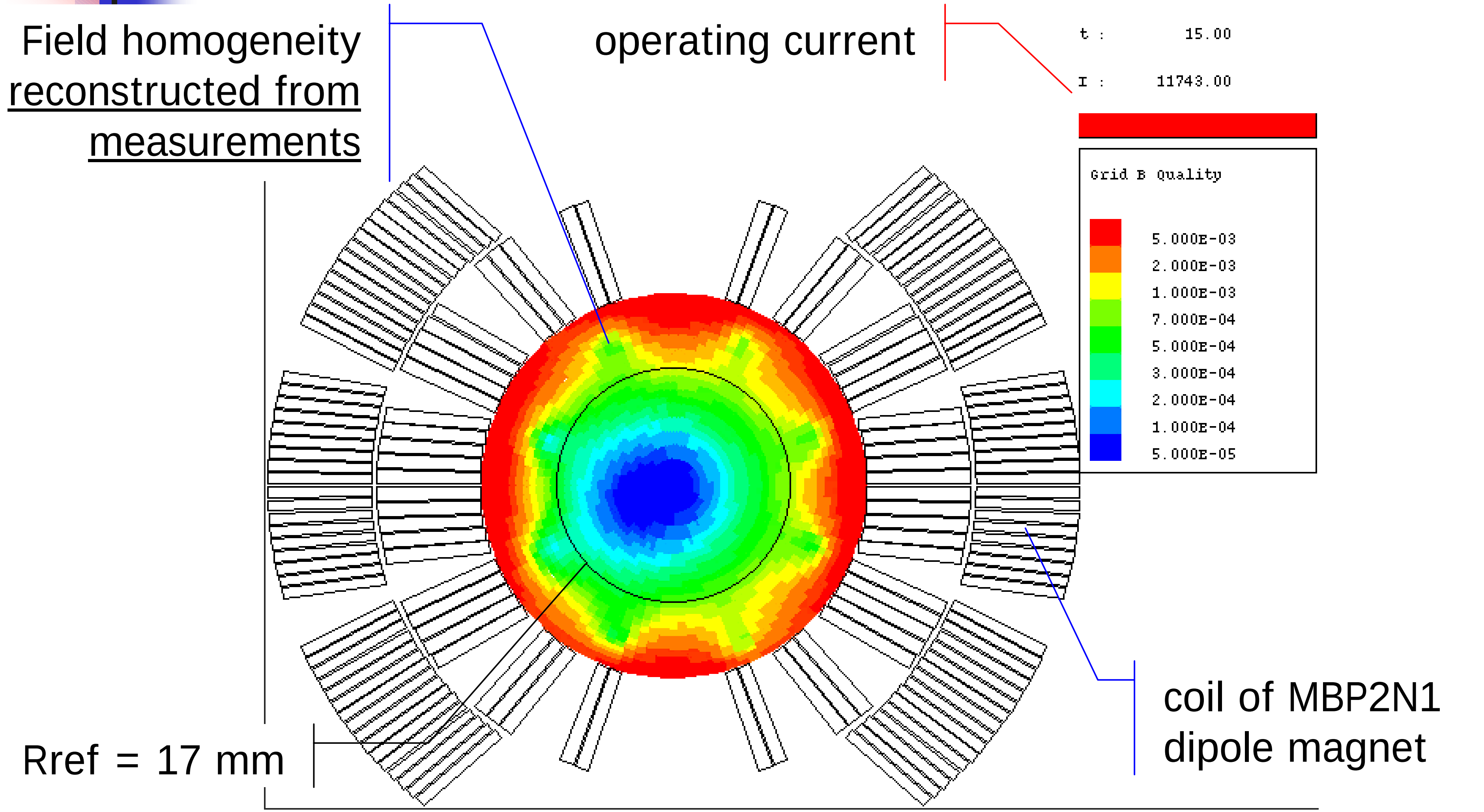
A Bit of Reality...

- Field quality reconstructed from measurements performed in MBP2N1
- Plot of homogeneity |B(x,y)-B1|/B1 inside the aperture of the magnet:
  - blue $\Rightarrow$ OK (1 $\times$ 10-4)
  - green $\Rightarrow$ so, so (5 $\times$ 10-4)
  - yellow $\Rightarrow$ Houston, we have a problem (1 $\times$ 10-3)
  - red $\Rightarrow$ bye, bye (5 $\times$ 10-3)

A typical LHC operation cycle



Sony Playstation III (*LHC tracking*)



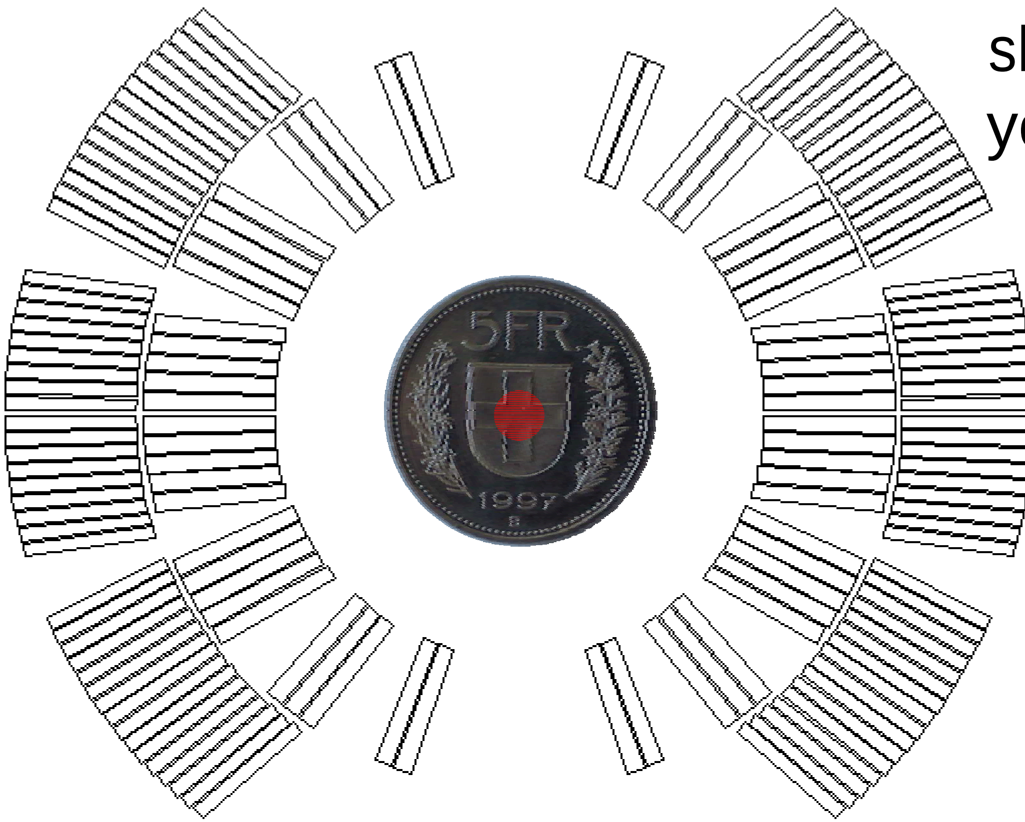
Is your arm steady ?

hit the cross of a 5 CHF coin...

at 30 km distance...

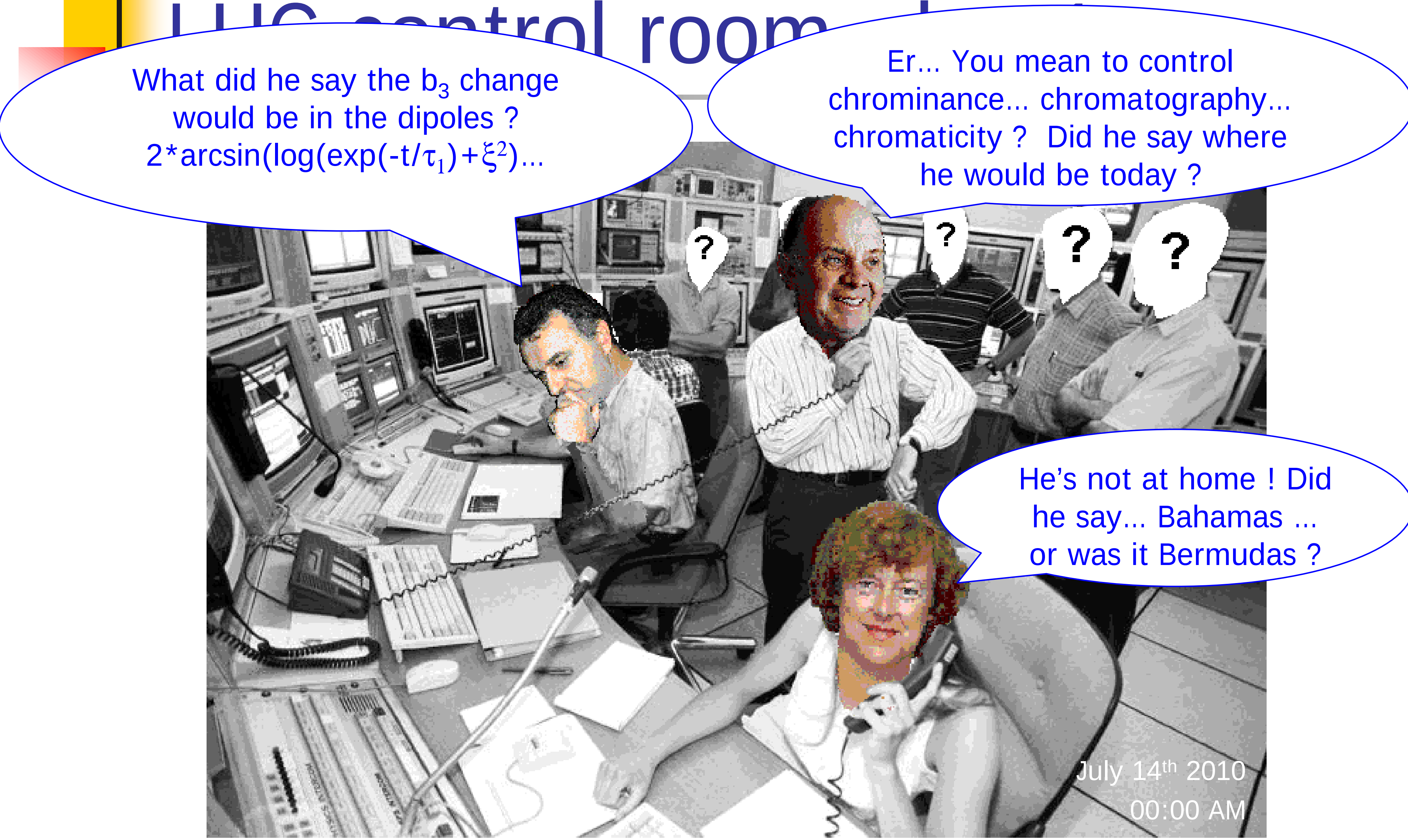
with a ≈5 mm thick laser...

shooting at your back !



... or book your vacations today

We will need a bunch of **very** intelligent guys to operate LHC...



and there are still vacancies in control room !